An Analysis of the Spectrum of 55 Cancri-e via Echelle Spectroscopy

An Honors Thesis (HONR 499)

by

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May 2019

Expected Date of Graduation

May 2019

Abstract

Presented is an attempt to measure the atmospheric composition of the transiting exoplanet 55 Cancri-e. This measurement was completed via the process of Echelle spectroscopy. All images were taken with the 0.9-meter telescope at Kitt Peak near Tucson, Arizona available to Ball State through the Southeast Association for Research in Astronomy (SARA) Consortium. All images were reduced using the Image Reduction and Analysis Facility (IRAF) software package.

Acknowledgments

I would first like to thank Dr. Kaitchuck for advising me during this project. Given all of the other projects he was already working on, I appreciate him taking the time to work on another.

I would also like to thank Jessica for working with me on this project and keeping me focused. We were regularly up very late for this project and ran into a number of problems with software. Nonetheless, she remained optimistic and broke the tense atmosphere with some humor.

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Process Analysis Statement

I would say the greatest lesson to be learned from this project is that patience is a virtue. Astronomy research is unique in the sciences in that it is the only field in which you cannot enter a lab and simulate the events that you want to study. Physicists, chemists, biologists, etc. all have the capability of isolating what they want to study and look at it in the luxury of whatever lab they want. This is not to degrade on any of those sciences, I want to be clear, but it definitely makes astronomy stick out from the rest. Not only can we not take stars and plants and put them on scales or wrap measuring tape around them, but we also must work within the confines of our own planet in order to study them. If our target is between the Sun and Earth due to the position of Earth's orbit about the Sun, then we simply must wait a few months. Likewise, with this project, if atmospheric conditions are poor, we must simply either wait it out or move to another night. However, unfortunately this only changes whether we are in Cooper until midnight or if we're there until seven in the morning.

Initially, my thesis project began in the Fall 2018 semester. However, for this project we require a specific telescope accessed through Ball State's membership in the Southeast Association for Research in Astronomy (SARA) consortium, for which we receive a finite number of nights each semester. As luck would have it (or possibly Murphy's Law), every night we had access to this telescope in the fall semester, was lost to poor weather conditions. Clouds would move in unexpectedly or rain would be close enough we would not be permitted to open the dome to the telescope, out of fear that the rain would move closer to the telescope (it takes time to close everything back up). We also suffer the problem of variable altitudes of the target system. In layman's terms, each night we observe our target, there is a different angle from the horizon at which our target appears in the sky (where zero degrees is at the horizon and ninety degrees is right above our heads). For the purposes of spectroscopy, we are limited to about thirty degrees and above in terms of altitude for good spectroscopy. Atmospheric conditions, as well as physical barriers such as trees and buildings begin to interfere with our data below this point, and thus nights where transits occur near or below this limit, we must consider whether the data would even be valuable or not.

These poor conditions actually forced a change in project after an entire semester was lost. My original idea for my thesis project was one based in photometry which required a lot more observational data than a spectrographic project would require, as spectroscopy has more work on the back end after data is collected rather than requiring more observations for the same quality of data, all else held constant. However, this is the nature of astronomical research and rarely does any project go without losing observation nights to weather. Fortunately, because we gain access to these telescopes through the SARA consortium, we receive a considerable number of observation nights throughout the year (approximately fifty or so nights every year), so if enough nights are lost to weather, we can still trade other available nights (between other astronomy professors at the university) to get access to the telescope we need.

Additionally, during the process of image reduction (acquiring the final spectrum that can be analyzed for the presence of an atmosphere), we encountered some setbacks with our image reduction software. Another common characteristic of astronomical research is that research software packages are typically very picky when it comes to how users interact and use the software (it is also typically very old). This is due to the fact that there are considerably fewer astronomers than there are physicists or engineers, and thus there isn't a solid industry for entire companies to form to develop easy-to-use software packages to distribute. Packages are usually developed by small groups of researchers or funded-organizations, and it's what we have to use in order to make life easier for the research. For this reason, documentation of the use of these software packages can metaphorically be worth their weight in gold, and IRAF is no exception. During our image reduction, we were following guidelines set by a previous student that used the same reduction software for a Master's thesis project previously. Despite this wealth of information we had regarding the use of this software package for echelle spectroscopy, we consistently ran into problems with the software that would cause it to crash a number of times.

For example, when flattening the comparison spectra, we would typically only proceed about four images at a time, because at about the fifth, it would simply crash. I do not believe it to be an exaggeration to say IRAF crashed over a hundred times in the course of our reduction, and when it crashes, it's not quite as simple as starting right back where you left off. You must close out all of the remaining windows, reopen a Linux command line, restart IRAF, re-run software packages, return to the correct directory to work from, identify what was saved and what was not, and then begin again. This process was justifiably maddening, and at times my advisor suggested that we step away from it until the next day because so many errors and crashes and frustration, at a certain point, simply inhibit clear thinking, which is absolutely necessary for scientific work. Eventually, we discovered that this was in fact an issue with the software we use to create a remote window to access our data from another computer, but by then the damage had been done.

Furthermore, with limited users of a software package and generally the inability to contact and troubleshoot with the writers of the package itself, some errors are simply unsolvable in a reasonable amount of time. For example, when flattening our flat frames, the image reduction software will automatically determine the width of each aperture, which is generally just ever-so-slightly too slim. This doesn't allow for *excess* noise, but it may exclude five or so percent of the measured light. However, for reasons only somewhat known (we know that an oversaturation of a few apertures had some role to play), the software was unable to recognize certain apertures and would thus not let us adjust the widths of said apertures. After a day or so of scratching our heads and yelling at the monitor, we simply decided to stick with the software's automatic aperture widths, as again they didn't include any light we didn't want, and it only excluded some miniscule fraction of the light, at least little enough that our advisor decided it wasn't worth the trouble on the timescale we were already reduced to.

Another example that ultimately led to defeat was during the process of identifying characteristic emission lines in the comparison lamp's spectrum. When we viewed the spectrum with the ability to mark features, each aperture was littered with lines and generally did not change in appearance, even from the first to thirtieth aperture. We expected the first problem on the first half dozen or so apertures because we knew ahead of time they were a little saturated, but the second was really puzzling, because our advisor had already worked with the comparison spectrum before, even using echelle spectroscopy, and thus we already had documentation of characteristic lines in each aperture, and there were definitely changes from aperture to aperture. We thought possibly the software had somehow inverted the plotting of the spectrum as a row plot instead of a column plot (which would show the saturation in every 'aperture' and thus show both the plethora of lines and the generally similar appearance in every image), but to this day we have been unable to solve that issue. For the purpose of actually finishing the project, we used a comparison spectrum from 2015, which our advisor stated would still be usable, because it was taken with the same camera on the same telescope with the same CCD, and comparison lamps should never exhibit a change in spectrum (otherwise that entire area of physics is utterly wrong).

That being said, I believe this project, problems included, was necessary for Jessica and me to grow as scientists. While I cannot say for her prior research experience, my other experiences in research went generally very smoothly, and it would be entirely wrong of me to continue forward in science thinking that scientific research typically goes smoothly and to never experience such frustration or issues, because problems like this are not uncommon, and to be good scientists, we need to be prepared to come up with solutions to these issues as they arise, and figure out ways around the problem, rather than simply throwing our forehead against the table and giving up. Additionally, the optimistic results of the project make me confident that a continued effort will result in an actual detection of an atmosphere around 55 Cancri-e, and it would make us one of the first astronomers *ever* to actually do so. When our research was presented at the Physics & Astronomy banquet in April 2019, a graduate student who will still be at Ball State next year was immediately interested in the project and told us that she would gladly continue our project. With that in mind, I would certainly call the project a success, as we have most definitely demonstrated that it is feasible for our university to detect an atmosphere around an exoplanet – a true demonstration of the quality of our telescopes through the SARA consortium – and we have garnered the interest of another student who is capable of expanding on the project even after we graduate. The continued research is what keeps our department going, as it is promising research that receives attention from the scientific community and grant money to fund future project and acquire better equipment, so I believe Jessica and I have certainly made an impact on our department with this project.

Introduction / Premise

When it comes to scientific research, the most important question for oneself to ask is why it is important and/or why it benefits the scientific community. Not only are both of those endeavors important to science, but research is only granted to what is deemed viable and important – whether it be done via a grant through an organization like the National Science Foundation or completed through the employment of some private sector company like SpaceX. In some cases, scientific research is presented or petitioned to groups or individuals outside the scientific community who may not immediately recognize the potential of projects, and for that reason, a reasonable justification for the outcomes of a project are vitally important.

In this case, the study of planets outside the Solar System is a relatively new endeavor. The first paper stating a discovered planetary system was in 1992[1] concerning a system of two large planets orbiting a millisecond pulsar. Since then, we have discovered some several thousand extrasolar planets (exoplanets). However, this research is a foundation upon which to better understand how our own planet came to be and possibly answer one of the longest-standing human questions in how/why we are here. If we are able to study how common other planets are or how commonly atmospheres exist on other planets, we might derive an understanding of how Earth got here and acquired its atmosphere. It's no secret that within the Solar System, Earth is a special case. There exist other celestial bodies in our star system, but typically very unlike ours – Venus, Io, and Saturn, to name a few. Additionally, only half of the terrestrial planets in our system have

[1] Wolszczan, A., & Frail, D. A. 1992, Nature, 355, 145-147

an atmosphere, and if we base our understanding of the universe on our system alone, then that's a bad case for the probability of acquiring an atmosphere.

Furthermore, aside from the indirect benefits of studying exoplanets generally, there is still an internal debate as to whether or not this planet specifically has an atmosphere. NASA itself still speculates as to what explains the measured surface temperatures of the planet[2] and thus such a project serves to settle an age-old question, and as NASA itself states, solving the mystery of what is leading to these temperatures could tap into the mystery of the evolution of terrestrial planets.

To provide some context, 55 Cancri-e is currently the closest planet to 55 Cancri, with an orbital period of less than a single Earth day. This orbit is in fact so close that it is tidally locked, meaning that the rotation of the planet and its orbit are synchronized such that the same half of the planet faces its star perpetually, and the other half is in a perpetual night. Astronomers have observed exoplanets like this before, and it intuitively leads to extreme temperature differences across both hemispheres of the planet, as a result of one getting permanent starlight and the other receiving none. However, data from the Spitzer Space Telescope, which observes in the heat-sensitive infrared region of the electromagnetic spectrum, suggests that the difference in temperature across both halves is not nearly as great as it should be.

As detailed in the NASA article, there are two dominant explanations for the observed surface temperatures on 55 Cancri-e: the first is that the planet is littered with free-flowing lakes of lava that both serve to reflect incoming starlight back into space

[2] Greicius, T. 2017, NASA (NASA), https://www.nasa.gov/feature/jpl/lava-or-not-exoplanet-55-cancri-e-likely-to-have-atmosphere

(cooling the hot side) and then cooling once they reach the dark side (warming the cool side). The second explanation is that the planet has a thick atmosphere that acts like our own – trapping some heat and reflecting the rest, which helps to maintain small thermal differences across both hemispheres of the planet, despite one receiving no sunlight. An analysis done by Isabel Angelo and Renyu Hu suggest that the latter is far more plausible for explaining the temperature difference on 55 Cancri-e[3], thus providing a solid basis for this project.

[3] Angelo, I., & Hu, R. 2017, The Astronomical Journal, 154, 232

An Introduction to Spectroscopy

In order to better understand the nature of this project, let us simplify the process of spectroscopy. Essentially, the study of an object's spectra allows one to determine the elements that compose the object itself. To understand *how* that process is accomplished, let us take a step back.

Many, if not all, are familiar with a scientific demonstration in which light is shone through a prism and seeing a rainbow of colors on the opposite side. That prism is breaking up a near-continuous spectrum into its component parts. Incandescent light almost perfectly emits a continuous spectrum, in which all 'colors' (wavelengths) of visible light are emitted equally. However, the variety of elements that have been discovered do not all exhibit continuous spectra, and each have a variety of different emitted wavelengths. The reason for this comes from the nature of emitted light from atoms in general.

One might have learned in a science class that when atoms produce light, it is because an electron becomes excited and moves to an electron shell further from the nucleus, and then emits light as it transitions back down. Effectively what is going on physically here, is that as electrons gain energy, once they contain enough to break free from its currently orbital shell, it will move to another available one with that energy, consuming the extra energy it has. This, however, is unstable, and thus it will transition back down, and release that energy as a photon instead. Because the energy of a photon is given by,

$$E = \frac{hc}{\lambda} \tag{1}$$

where E is the energy of the photon, h is Planck's constant, c is the speed of light, and lambda is the wavelength. The wavelength (and thus, the color) of the light can be derived from the energy of these transitions. In this case, the energy of the transition can be described through the forces involved. Here, the force involved is the electromagnetic force, which is proportional to the charges of the two bodies, and inversely proportional to the distance between them squared. What changes is the charge on the second body (as the first is *always* a single electron), and differing atoms have larger or smaller nuclei (and thus larger or smaller positive charges) and this difference is what leads to different energies in the transitions. However, it is important to note that these transitions occur at discrete values.

The Franck-Hertz experiment in 1914 demonstrated that electrons occupy only discrete, quantized energy states, which not only lent credit to the Bohr model of the atom, but assures that these transitions, based on which energy states these electrons transition between, are predictable and quantized. This relationship was later described by the Rydberg Formula, given as,

$$\frac{1}{\lambda} = R_H \left(\frac{1}{n_1^2} + \frac{1}{n_2^2}\right) \tag{2}$$

where λ is the wavelength of the photon in a vacuum, R_H is the Rydberg Constant (approximately $1.097 \times 10^7\ m^{-1}$), n_1 is the orbital level the electron occupies prior to the jump back down, and n_2 is the orbital level the electron occupies after it 'jumps' and a photon is emitted.

Now, we effectively have a way to measure what types of elements are present in a system by measuring the light being emitted from that system, because the wavelengths of that light correspond to a variety of identifiable elements. As a brief example, notice the differences between a continuous emitted spectrum, and the emitted spectrum of a hydrogen gas in Figures 1 & 2, respectively:

Fig. 1 The continuous emission spectrum of light.

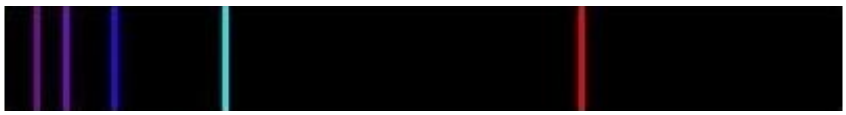

Fig. 2 The emission spectrum of hydrogen.

Thus, in a simpler fashion, if one is looking at the emission spectrum of an object, and notices these lines, he/she can deduce that hydrogen is a constituent element of the object. As it might be expected, such a process in practice is much more complicated, as there will be emission lines from far more than a single element, and these lines can vary depending on whether or not the element has been ionized prior to being observed, if the object is moving, or if the light has also passed through some gas, to name a few. Because stars and planets spin, corrections must be made to spectra because the movement creates Doppler shifts in the spectral lines, a phenomenon in which movement of the object emitting the light changes the wavelength of the light. Most stars are also hot enough to ionize at least a few elements once or twice, and then all light that reaches Earth from outside the Solar System must pass through the Inter-Stellar Medium (ISM), which is comprised of a variety of gases which alter the spectra of incoming light. As an example, shown below is the absorption spectrum of the Sun:

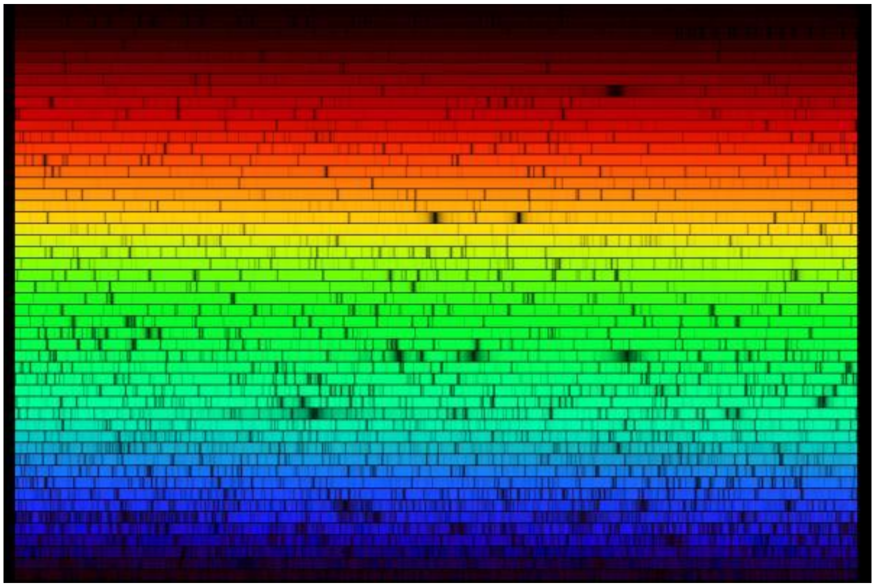

Fig. 3 The absorption spectrum of the Sun. The resolution of the spectrograph used requires that the spectra be spread over many lines, as one line would far exceed a monitor's view.

It is important to note here that previous examples were of emission spectra, and this is an absorption spectrum. However, it is simple in that the inverse of an emission spectrum is the absorption spectrum, and vice versa. This is due to the fact that emission spectra measure what wavelengths of light are emitted by a particular element (and all other wavelengths are absorbed), and thus inverting the colors shown and the colors blacked out demonstrates the same element's absorption spectrum. As stated before, the spectrum of the Sun (and any star) is far more complex than that of a single element such as hydrogen, as many of the elements present in the Sun have far more numerous numbers of spectral lines, and some elements could have been ionized more than once, resulting in even more lines present.

The Operation of Spectrographs

It is also important to understand how we as observers capture and measure the spectra of stars before discussing what specific spectra mean for the star. Obviously when looking out at the night sky, one cannot see the continuous spectrum of light with only a few characteristic lines– most stars appear largely yellow-white, red, or blue. In order to determine the precise spectra of these objects, we must collect their light through a spectrograph mounted on a telescope to be able to collect enough light from so far away.

Light from the target star will enter a small slit in the focal plane of a telescope into the spectrograph, where it will reflect off a special kind of mirror – called a collimating mirror – that will align all light rays parallel to one another. These parallel light rays will then reflect off a diffraction grating, which will cause different wavelengths of light to reflect off it at differing angles. This occurs because diffraction gratings contain some form of periodic structure that induce position-based phase or amplitude changes. In the case of reflection gratings, used in spectrographs, the periodic structure is some form of surface relief that induces position-dependent phase changes that follow the grating equation:

$$asin(\theta_m) = m\lambda \quad (3)$$

where a is the distance between surface reliefs, theta is the angle of the reflected beam of light relative to the normal at some m^{th} order, m is the integer corresponding to the order of diffraction, and lambda is the wavelength of the light. This equation demonstrates that the angle at which light reflects off a particular surface relief on the grating corresponds to a particular wavelength or color. This phenomenon is shown in Figure 4 below:

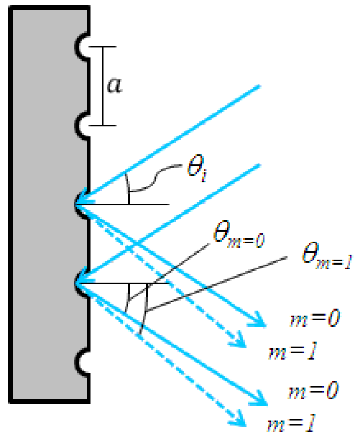

Fig. 5 An example of the process of light reflecting off a diffraction grating.

This light is then reflected onto a photodetector, where it converts different photons into electrical signals where eventually a wavelength will be determined. This photodetector today is typically a Charge Coupled Device (CCD). CCD's are broken up into incredibly small areas called pixels, and when photons strike a pixel, it is converted into one or more electrons, and the number of electrons at each pixel is directly proportional to the intensity of the scene at that same pixel. The entire process from start to finish in a spectrograph is detailed in Figure 5 below:

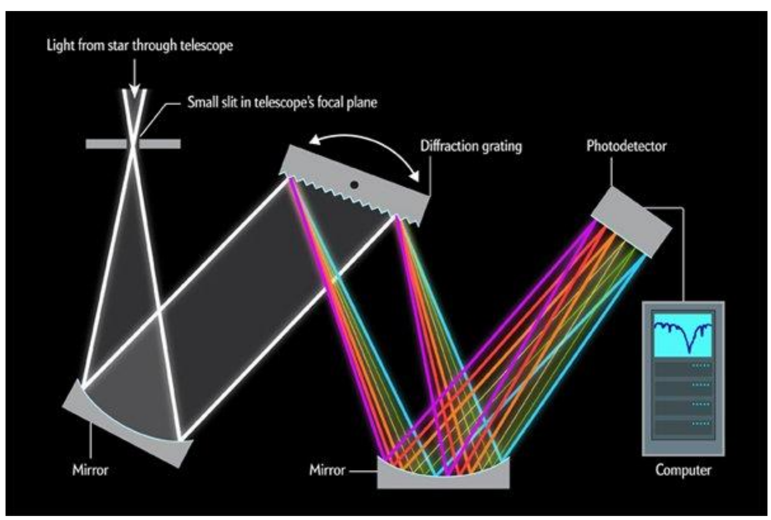

Fig. 5 An illustration demonstrating the operation of a spectrograph.[4]

[4] Jabr, Ferris. "How Does a Spectrograph Work? [Infographic]." *Scientific American*, 1 Dec. 2012, www.scientificamerican.com/article/ancient-stars-how-does-spectrograph-work/.

While most spectrographs are not quite this simplistic, it provides a basis for which to understand how this data is collected for use.

Echelle Spectroscopy

There are several designs to spectrographs that achieve the same basic thing – the collection and dispersion of light. For this project we were using a particular type of design called an echelle spectrograph. Here, 'echelle' refers to the French word for 'ladder' and is indicated in how the resultant spectrum looks when collected. Echelle spectrographs disperse light in two orthogonal directions, rather than in one direction, by using a combination of two diffraction gratings or two prisms to disperse the light. This process allows for both high spectral resolution as well as a large bandpass. Think of the spectral resolution as how well the spectrum is able to differentiate between small differences in wavelength, and the bandpass as how large of a range of wavelengths that is able to be measured.

As a result, this spectrum is quite long and is typically shown as multiple lines aligned vertically (hence the similarity to the look of a ladder). In fact, the solar spectrum in Figure 3 is an example of a spectrum from an echelle spectrograph. While most spectra can display all colors of the visual spectrum on a single line, Figure 3 shows individual colors spanning multiple lines, which is indicative of the high spectral resolution of the spectrograph. The fact that the spectrum spans from red colors at the low-frequency end of the visible spectrum to blue/purple colors at the high-frequency end demonstrates the large bandpass of the spectrograph. This preservation of both high spectral resolution and large bandpass makes echelle spectrographs particularly useful for astronomy, as information can be gathered from all regions of the visible spectrum, but in other spectrograph designs, a high bandpass requires a lower spectral resolution, which can lead to greater inaccuracies and higher uncertainties in acquired data. An example of the optical design of an echelle spectrograph can be seen from the Mechelle 5000 spectrograph from Andor Technology:

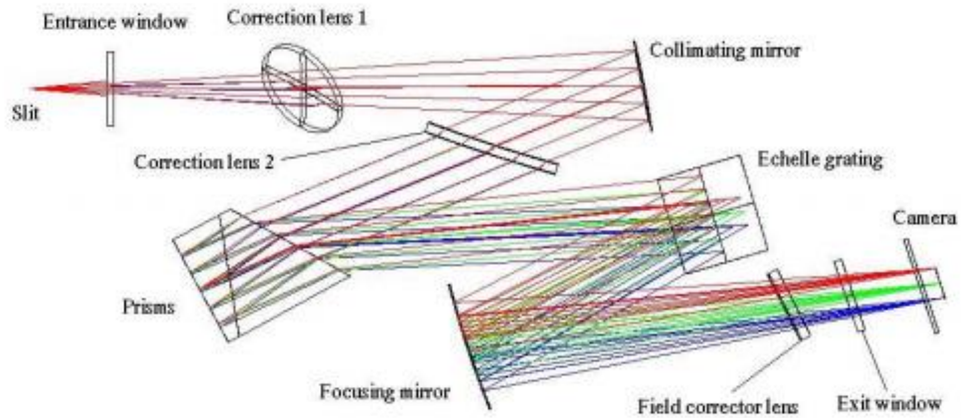

Fig. 6 The optical design of the Mechelle 5000 spectrograph.[5]

The resultant image from this design of spectrograph is two-dimensional in nature, however, as seen in the solar spectrum in Figure 3, and thus is ideally captured with a two-dimensional detector like a CCD camera. This then introduces limitations on imaging based on the quality of the CCD. Fortunately, the spectrograph and CCD's at SARA's Kitt Peak telescope are of considerable quality, due to the spending power of a number of universities in the same consortium that manage and operate the telescope.

[5] "Echelle Spectrographs - A Flexible Tool for Spectroscopy - Andor Learning Centre." *Oxford Instruments*, andor.oxinst.com/learning/view/article/echelle-spectrographs-a-flexible-tool-for-spectroscopy.

Observations

Our observations of our target took place over the night in several stages. In order to accurately determine the presence of an atmosphere about the planet, we needed two measurements: the spectrum of the star system when a transit of the planet was not occurring, and the spectrum when the planet *was* transiting. The thought is this: when 55 Cancri-e is not transiting, you'll simply have the spectrum (and thus the elemental composition) of the host star. When it *is* transiting, you'll have the elemental composition of both the host star *and* the atmosphere of the planet, if there is one. From this, in theory, the atmosphere of the planet can be obtained through a subtraction of the first spectrum from the second.

Using this methodology, we needed observations within reasonable parameters. Chiefly, we needed observations on nights with low atmospheric 'seeing' conditions and a high altitude during the transit. The 'seeing' conditions during astronomical observations indicate the level of turbulence in Earth's atmosphere and greatly decrease the quality of astronomical imaging, especially with increasingly-large telescopes. A common indicator of the seeing conditions without using astronomical observation tools is to observe how 'twinkly' the stars are at night. The scintillations of the stars (the twinkling) is due to turbulence in the upper portions of the atmosphere, and thus greater levels of twinkling indicate worse seeing conditions. The transit occurring at a high altitude is also due to minimizing the effects of Earth's atmosphere on our imaging capabilities, given that we are collecting data from a ground-based telescope. Incoming light from directly above the observer (corresponding to an altitude angle of ninety degrees) passes through the smallest amount of atmosphere, and light passing through any horizon (an altitude angle of zero degrees) passes through the most amount of atmosphere. As per my advisor, we restricted our observations of transits to those that occur at altitudes of thirty degrees and above, to maximize the quality of our data. The transit is most important because it only occurs at particular times and only on certain nights at times when we can collect data. The spectrum of the star itself is much easier to gather because it passes through the sky every night at this time of year, and thus we are afforded much more flexibility in gathering that data.

On nights in which all necessary precursors are satisfied, we begin by accessing and preparing to use the remote telescope operation, because the telescope we're using to gather the data is located at Kitt Peak National Observatory near Tucson, Arizona. We then access remotely specialized software for operating the telescope through a graphical user interface (GUI). When weather conditions have been cleared and we are able to observe, through the interface we are able to open the dome of the telescope, enter the astronomical spatial coordinates of our target, and the telescope guides itself to our target.

When this is complete, we now must ensure that we are focused on the correct star field and assure that the tracking system of the telescope is working. Typically, this is done by visually observing the correct star field via a third-party application and comparing it to the field we see before us, as it may be rotated in some fashion as well. Once we are confident that we have targeted the appropriate star, we focus the telescope and the spectrograph, ideally using some source of bright light. However, this is not always possible. For example, on the evening of March 2nd, we were observing just after the Charles Brown Planetarium scheduled an event called "The Real Universe In Real Time" in which the astronomers used access to all three of the telescopes we use through the SARA consortium to show the public astronomical imagery in real-time. Because of this, by the time we gained access to the telescope for our own use, it had already darkened considerably, and the phase of the Moon that night was virtually new, such that there was not an ideally bright target, and the focusing of the spectrograph was less than ideal. This issue reared itself later in the observation.

When both the telescope and spectrograph have been focused, we may now begin to observe our target over whatever exposure length we so desire. The exposure length, like with regular cameras, dictate how long the CCD collects light from the primary mirror of the telescope, which is reflecting the light from the star onto said chip. For the purposes of this project, we began with a five-minute exposure to see how well it would perform, and after several exposure we increased the time to ten minutes per exposure. When it comes time to actually perform this operation, however, there are two options: the first is to allow the spectrograph to guide itself, and the second is to guide it remotely (far more tedious). Unfortunately, due to the issue earlier of the spectrograph being less-than-ideally focused, we were unable to guide the target with the spectrograph automatically, and thus were forced to guide the spectrograph remotely for the duration of the observation. To make matters more interesting, the field itself was inverted at an approximately forty-five-degree angle, so the controls for guiding the entrance port of the spectrograph were entirely counterintuitive. Buttons oriented in the horizontal direction would move the slit in the four cardinal directions, and the buttons for the cardinal directions would move the slit at some angle. Coupled with the lack of sleep and early-morning hours, the process was annoying to say the least. Additionally, throughout the observation it is important to take images of a comparison lamp made with thorium and argon to use.

When we are finished with exposures of the target, there are still measurements to be made. Measurements must still be made of what are referred to as the darks, flats, and biases. The dark frames can be likened to the zeroing of a scale, as it removes any thermal emission from the pixel that should otherwise not be there. Not all pixels on a camera are identical; some will read hotter signals, some colder, just in general not read the same signal in the same way. The dark frames are meant to capture that imperfection across the chip by taking an image with the camera shutter kept closed to prevent any light from getting in. This then provides an image of what total 'darkness' should look like, which is rarely (if ever) totally dark. Typically, several dark frames are taken to reduce inconsistencies or possible leaks of light and, have the bias frames subtracted, and are then subtracted from the object frames (the images taken of the star) to eliminate the inconsistencies in signals across the chip.

The flat frames are similar to the dark frames in that they're likened to zeroing a scale, but these eliminate optical inconsistencies, rather than those of the camera sensor. Telescopes often don't even distribute light evenly across the sensor, and this results in excess light in the center of the sensor and less light at the edges. To remedy this, images are taken with a blank, even illumination across the whole sensor, which should even-out the illumination across the object frames.

Finally, the biases are meant to remove the readout signal from the sensor. The way in which the camera reads out from the sensor will vary, even if individual pixels have not received signals, and subtracting the bias frames removes that variation. They're gathered by taking an image with an exposure time of zero with the camera shutter closed. Examples of all taken images can be seen in Figures 7-11, respectively. With our object frames, flats, darks, biases, and comparisons, we are ready to reduce our images for analysis.

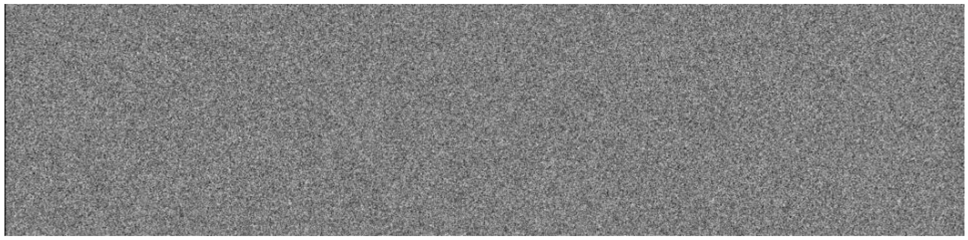

Fig. 7 An example of a bias image.

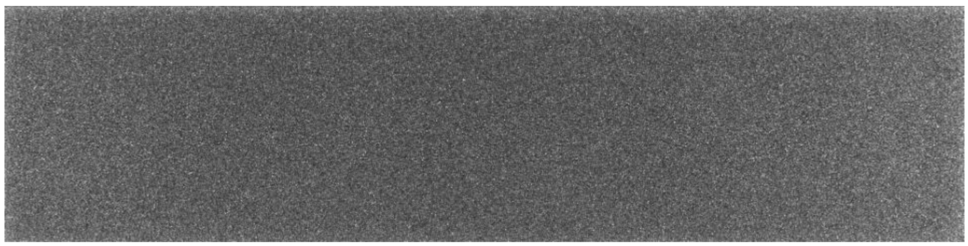

Fig. 8 An example of a dark image. Notice that even with the camera shutter closed, there is still some noise.

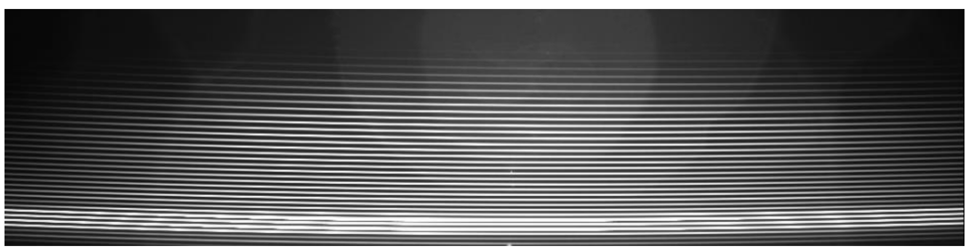

Fig. 9 An example of a flat image. The consistency in light across each row is indicative of the uniform light across the CCD.

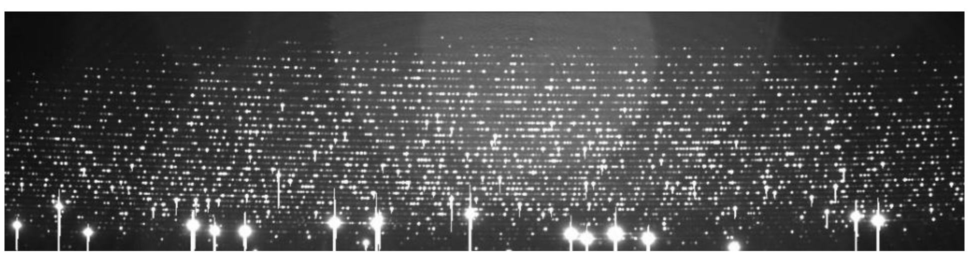

Fig. 10 An example of a comparison spectrum. The large, bright circles towards the bottom of the image are regions in which the CCD was oversaturated with light. This spectrum affirms the complexity of real spectra as mentioned earlier.

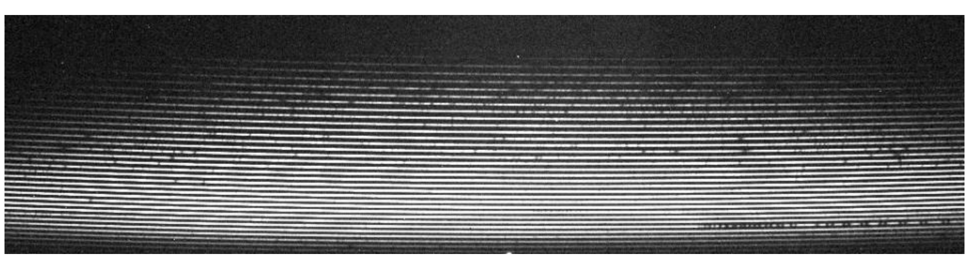

Fig. 11 Finally, an example of the object spectrum used in our project. Because stars emit light at so many wavelengths due to their plethora of elements, it is far closer to a continuous spectrum than the comparison spectrum. However, it is not quite as complete as the flat frame.

Image Reduction

The reduction of our images is meant to filter out the unwanted noise discussed previously regarding the bias, dark, and flat frames, as well as actually subtract the spectra of the star in and out of transit to acquire a spectrum that is actually useful. This does not require the use of any kind of specific hardware, however. It is instead done on a computer using the Image Reduction and Analysis Facility (IRAF) software package, a Linux-based image processing suite. There are a number of accessible software packages for image processing, however for echelle spectroscopy, IRAF is one of – if not the – best available option. Our image reduction occurred in several stages.

In the first stage, the images are prepared for the process of correcting the object frames for unwanted noise caused by the number of inconsistencies in the hardware. IRAF is capable of processing multiple images at once, and thus it is inefficient and needless to apply the same process one image at a time. To achieve this, in Linux we create a list file for each type of image we have – bias, dark, flat, object, and comparison. It simply creates a file that holds a list of all the images in a particular directory. One important note is that our object frames are contained in two list files – one containing images while the planet was transiting, and one containing images when the planet was not. During our observations, we recorded the time at which each image was taken and based on the duration of the transit acquired from a NASA database and the time of mid-transit, we are able to determine what range of times corresponds to the planet being in transit.

Additionally, for some frames, it is better to make a single image that contains simply the average of the constituent frames, because making separate corrections for each frame is unnecessary, and correcting based on the average is better than correcting based on one frame, because a single frame may be an outlier. IRAF has some built-in tasks to achieve this, and thus we made an average bias, dark, and flat frame to use for our processing.

In the next stage, we actually prepare the object and comparison frames for the actual subtraction and analysis. IRAF has another built-in task for adding or subtracting (whichever is appropriate) the corresponding light from each pixel on both the comparison frames and object frames. We must then 'tell' IRAF where each aperture (or order) lies on the CCD chip. IRAF has a task called 'apflatten' that maps the location of each aperture by creating a function-fit to each aperture of the flat frame (because each pixel that collects light is uniformly saturated, ideally). This process at the beginning and during the function fit can be seen in Figures 12 and 13, respectively:

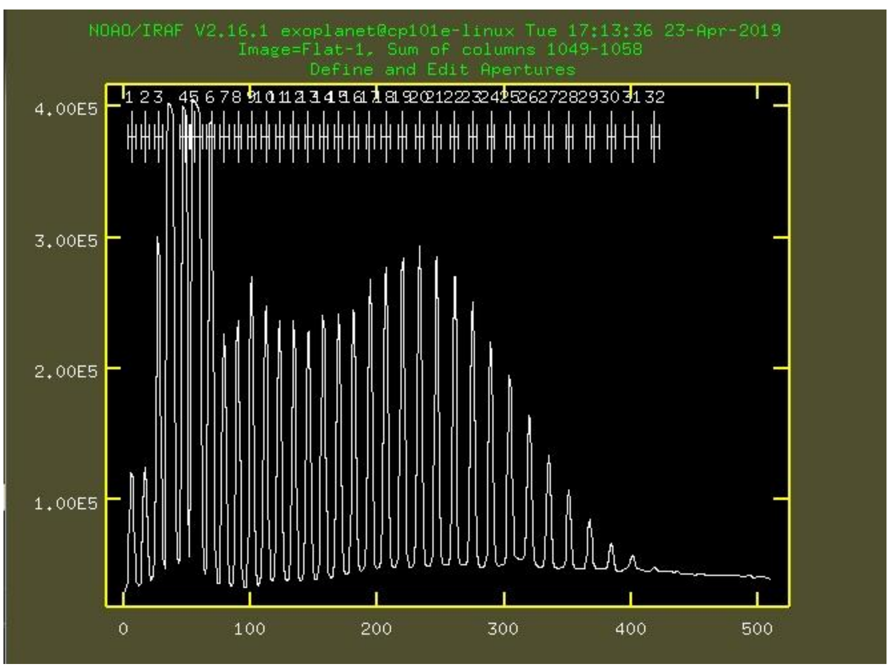

Fig. 12 The image seen at the beginning of the 'apflatten' process. Each spike in intensity corresponds to a separate aperture, of which there are 32. At the top, each labeled number indicates the recognized aperture, with the smaller lines indicating the width of the aperture, and the large line being the center.

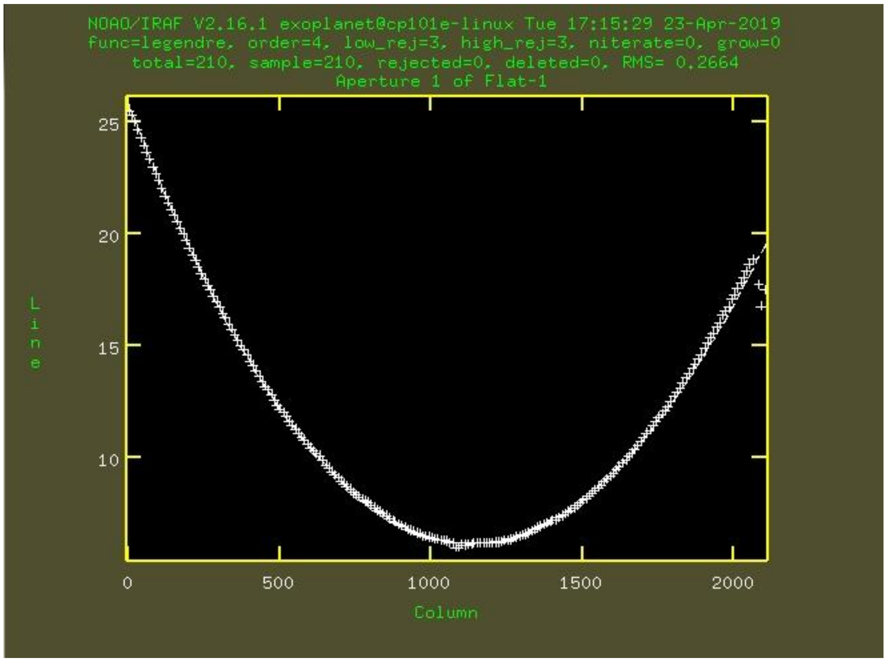

Fig. 13 An example of the function fit in the 'apflatten' process. On the far-right side of the plot, past the 2000 column mark, a line is visible, which indicates the best fit line for the aperture. As it can be seen above the plot, we used a Legendre function to fit the aperture.

This process can be tedious if one wishes to collect the maximum amount of light, but it must be done regardless, because if not, when processing the comparison and object frames, if IRAF does not accurately know the locations of the apertures, then excess noise could be measured, or important data could be excluded. Unfortunately, some of our apertures *were* saturated, and thus we did not have the luxury of re-adjusting the aperture width to maximize the light gathered. Fortunately, though, IRAF is surprisingly good at detecting the apertures on their own, and my advisor stated that we were fighting the program (IRAF would continuously crash on us when we attempted to adjust the width of the saturated apertures, causing us to have to reload *everything* associated with IRAF, which can be a lengthy process) for only 5% to 10% more light, and thus we left the aperture measurements with what the program deemed to be there.

We then had to provide IRAF with a wavelength range for each aperture. The CCD doesn't inherently know what wavelength of light is hitting each pixel exactly, and the precise location of each wavelength is vital to recognizing the spectrum of the object. When the CCD presents data, it is a plot of the relative intensity of the light striking a particular column (corresponding to a pixel on the chip). This is not a problem, however, because we have the spectrum of the comparison lamp taken with the same camera which would measure the same light in the same locations on the CCD. Because we know the exact composition of the spectrum of the comparison lamp, we are able to determine a wavelength range of each aperture by identifying characteristic lines of the spectrum of the lamp. This, however, is easier said than done. Our advisor previously spent approximately two weeks on a previous spectroscopy project to determine which apertures corresponded to which characteristic emission lines, and the precise wavelength of each emission feature. Our job was to go through all thirty-two apertures, ensure that the emission lines matched those of his previous measurements, then mark each feature and assign the appropriate wavelength to each feature. Some apertures were relatively easy, containing only a few important features. Others, however, may contain ten or more features that must be carefully marked. However, with this complete, we then had a method of determining the wavelength range of each aperture. Using IRAF, we were then able to assign the same wavelength ranges to the object frames, because those images were captured with the same camera and would have an identical range of wavelengths on each aperture.

When that was completed, it was then time to flatten and normalize the object frames. When the excess noise and inconsistencies are corrected for, one is still left with a curved spectrum, and while that is technically usable, it is generally accepted that more identification mistakes are made when using curved spectra than normalized ones. This process is done with a polynomial fit to the spectra to (ideally) eliminate or mitigate signal noise in the spectrum.

There are now two spectra: a flattened and normalized spectrum of the star while a planet is transiting, and a spectrum of the star while the planet is not in transit. From here, IRAF contains a simple 'imarith' (image arithmetic) function to add, subtract, multiply, etc. spectra, and simple subtraction of the out-of-transit from the in-transit spectra is necessary. However, we also made a subtraction of the unnormalized spectra, and then divided by the out-of-transit spectrum to achieve a normalization of the frame without a polynomial fit, using the literal spectrum itself as the normalization technique. The image processing is now complete, and we are left with a flattened, normalized spectrum, shown in Figures 14 & 15. All that is left is to identify characteristic lines of an atmosphere. This is much easier said than done.

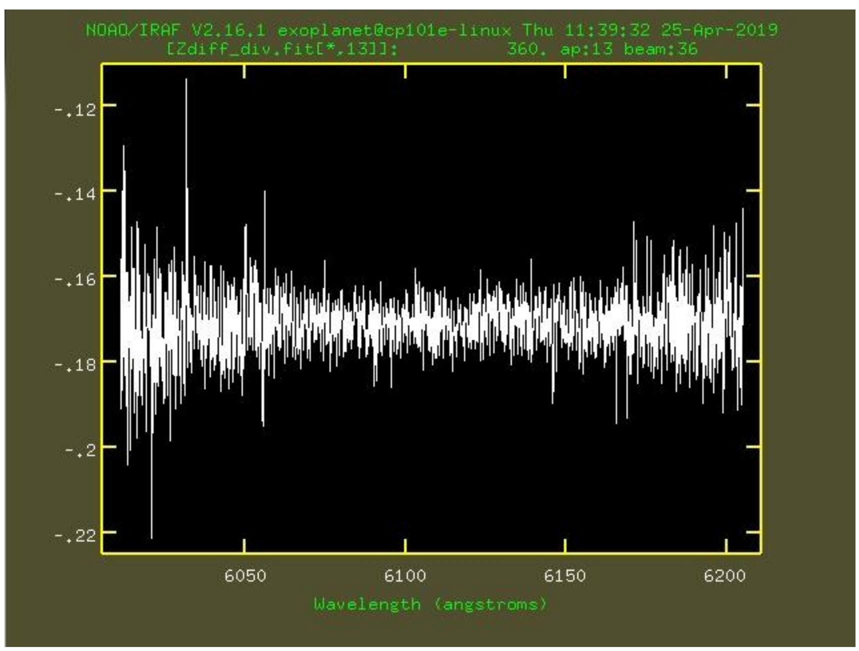

Fig. 14 Aperture 13 in the normalized, subtracted spectra. There are some possible emission features here, but this is largely noise in the ~6000-6200 Angstrom region.

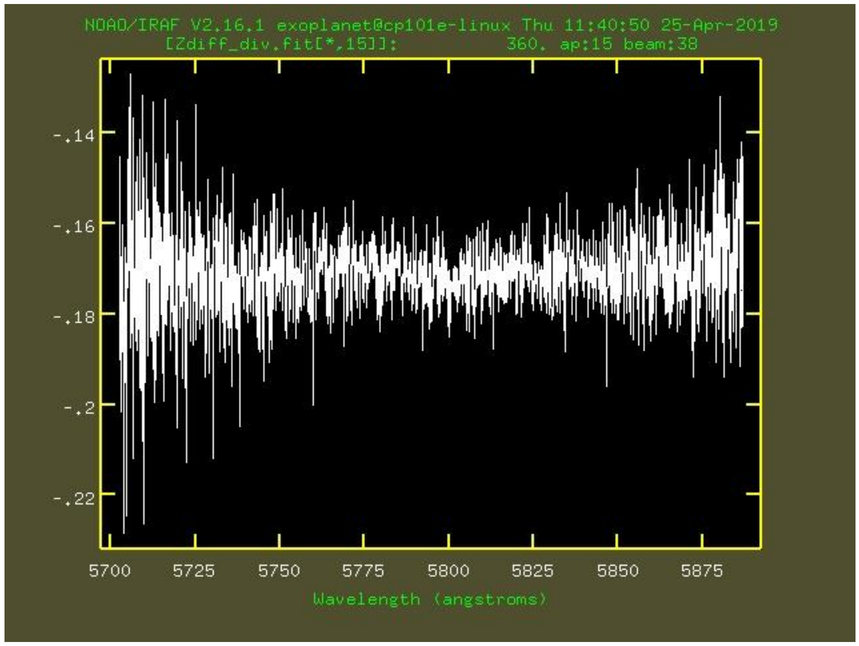

Fig. 15 Aperture 15 in the normalized, subtracted spectra. Of note is the gap in the 5800 Angstrom region.

Analysis and Conclusions

Regarding the analysis of the resultant spectrum, there is no complex scientific hardware or software. Because we are looking for features indicative of the presence of an atmosphere without knowing if there is one yet, this is simply a visual inspection to try and sift through the noise. However careful one is to try to mitigate noise in spectral data, there will inevitably remain some noise that is totally useless, and at the end of the day, this is a search for an atmosphere. To put it into perspective, you're searching for the presence of something typically less than one percent of the planet's diameter, which itself is less than one percent of the diameter of the host star, which is many light years away, with a telescope on another planet.

That being said, there is currently nothing conclusive about the presence of 55 Cancri-e's possible atmosphere. An optimistic sign, however, can be seen in Figure 15. At the 5800 Angstrom mark, there is a gap in the noise on the upper end of the spectrum, indicating an absorption feature. This feature is very possibly a sodium D line. Additionally, a paper published in the Astrophysical Journal demonstrates that sodium is also present in Earth's upper atmosphere,[6] which could indicate that we have in fact detected an atmosphere around the planet.

However, as with everything in science, it is important to stay grounded when making conclusions from research. Further observations from Ball State will be needed to see if these features and any other future features we discover remain in future spectra, and ideally, observations from other groups will also affirm the results found by Ball State. That being said, I think it would be irresponsible as a scientist to make a definitive

[6] Cabannes, J., Dufay, J., & Gauzit, J. 1938, The Astrophysical Journal, 88, 164

statement regarding the success of actually detecting an atmosphere. At the same time, this project was proposed as a means of examining the feasibility of detecting an atmosphere at all with Ball State's telescopes. With the initial results we have received from this project, as well as the comments made by my advisor, I believe that *that* portion of this project was a total success, and my advisor believes that with continued observations, an atmosphere, if it is present, will almost certainly be detected. Unfortunately, as a Ball State senior, I will not be the one to accomplish said detection, but given that such optimistic findings were presented at the Ball State Physics & Astronomy banquet at the end of April 2019, I am confident that a younger student interested in astronomy and astrophysics will continue this project after Jessica and I graduate.

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